Modelling of diesel particle filter pressure drop in the presence of passive and active filter regeneration

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Abstract. Diesel Particulate Filters (DPF) has now been proven as an efficient solution in order to reduce Diesel PM emissions. Concerned by environment, Renault will equip all serial production Diesel vehicles with this technology. Main issue of such devices is the mandatory periodical regeneration in order to eliminate their soot content. The particulate filter (DPF) is used to store the soot emitted by the motor combustion. When the mass of particles in the filter reaches a certain limit mass, it is regenerated thanks to a temperature rise (Over 600°C). In this paper, we develop a model that describes the impact of the amount of soot in the filter on the Diesel engine performance. This model is used to determine the optimal amount of soot on which the regeneration of the particulate filter shall start. Then we propose a physical model that describes the pressure drop of particulate filter according to the mass of accumulated soot and inlet DFP temperature and flow conditions. Thus, we improve a literature model so that it takes on account the passive regeneration of the filter. The experimental validation is made thanks to different test means: engine dynamometer, chassis dynamometer and vehicles.

Keywords: Combustion engine, particulate filter, pressure drop, porous wall, thermal, active regeneration, passive regeneration.

1 Introduction

The regeneration or purge operation is to burn soot on particulate filter in order to restore its original characteristics (efficiency, capacity, pressure loss): this involves alternating loads and purges throughout the life of vehicle. Normally, the complete regeneration (via oxygen) is possible only if the trapped carbon temperature is high enough (at least 550-600 $^{\circ}C$) and if the partial pressure of oxygen is sufficient (beyond 11 to 12% of O_2). It can be held by two processes, thermal (heating techniques external to the engine and / or interventions on the engine itself) and / or catalytic, and requires a strategy for controlling the regeneration (detection of the load, triggering, monitoring and clipping of the regeneration sequence). If the filters are overloaded, the particles can cause obstruction of the flow of gas, which is manifested by an increase of the particulate filter pressure drop. We can go until the clogging of the filters. Thus, the filter may be regenerated before the problem occurs. The DPF system must operate autonomously, that's mean that neither the driver nor the after-sales service should be asked to interfere except for a thorough cleaning of the filter at a very low frequency (1-2 times per year maximum). During regeneration, the soot is oxidized into gaseous products. Temperature is the most important parameter of regeneration. At low temperatures (360 $^{\circ}C$ to 400 $^{\circ}C$), the oxidation rate is very slow and regeneration is incomplete. Beyond a temperature of 600 $^{\circ}C$, soot oxidizes rapidly and completely. Thermal regeneration of DPF requires a temperature of 550 $^{\circ}C$ to 600$^{\circ}C$. Necessary temperature for regenerating the DPF is not reached at the exhaust of diesel applications (300$^{\circ}C$ to 450$^{\circ}C$ for trucks, and 200 $^{\circ}C$ to 300 $^{\circ}C$ for light commercial vehicles:). It is thus necessary to facilitate the regeneration by increasing the temperature of exhaust gas [1] and / or by getting the ignition temperature of soot lower by use of catalysts. The control performance requirement is derived from the filter sensitivity to inlet temperature. As described previously, active regeneration is mainly characterized by the soot combustion speed: a lower regeneration speed will lead to higher fuel consumption and oil lube dilution penalty, while higher regeneration speed will endanger DPF itself. As the speed of the combustion is governed by chemical kinetics and hereby by filter inlet temperature, combustion speed control window can be derived into inlet temperature control window. The control window defines a speed range where combustion is efficient for a limited lube dilution and fuel consumption penalty. The higher the soot mass in the filter is the tighter in the bandwidth. The modeling of the internal DPF temperature [2] and soot mass during an active regeneration event allows determining minimum and maximum inlet temperature for each initial soot mass load ensuring DPF integrity while maintaining high efficiency. Using this model, maximum internal filter temperature is monitored for a wide range of soot mass and DPF inlet temperatures combinations. This temperature is then compared to DPF supplier recommendations, leading to following description see figure 1.

Soot load capacity target, which is defined by the maximum soot load allowed in the filter while maintaining safe and efficient regeneration in all driving conditions leads to thermal control target.

The regeneration of the particle filter is made when the weight of soot in the filter reaches a limit value which we call SML (Soot Mass Limit). The SML is calculated so that the pressure drop due to the presence of soot in the filter does not reduce engine power in a significant way.

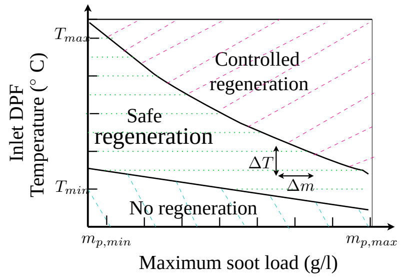

Fig. 1. Active regeneration Control Window

2 Study of the impact of the mass of soot on the performance of internal combustion engine

The power supplied by the engine is the effective power collected on the shaft ($W_e^{ENG,out}$), it is equal to the power developed by the cylinders (W_{cyl}) minus the losses due to the friction. We introduce the mechanical efficiency η_{org}. This efficiency takes into account friction losses and mechanical power required to drive necessary engine accessories. It can be defined as the ratio between the effective power and the power transmitted by the real cycle to the piston (W_{cyl}). The effective power is by definition a function of torque $\varGamma$ provided on the shaft and the rotation speed N. The power developed on the driving shaft is equal to:

$$W_e^{ENG,out} = 2\pi \frac{\varGamma N}{60} = \eta_{org} W_{cyl}$$

W_{cyl} is determined by the expression (4 stroke engine):

$$W_{cyl} = \frac{1}{2}\frac{N}{60}\oint pdV \tag{1}$$

where p and V are pressure and volume of engine gases.

When the particle filter is loaded, the pressure drop across the filter increases, so that the engine has its outlet pressure increasing and hence its output power decreases.

We adopt the following notation:

- P_{adm} pressure of the air intake;
- $P_{exhaust}$ gas pressure in the engine exhaust;
- $P_{compress}, P_{comb}$ and P_{exp} gas pressure in the cylinder after compression, combustion and expansion;
- P_{cyl} gas pressure in the cylinder.
- R air/ fuel ratio

Equation (1) become:

$$W_{cyl} = \frac{1}{2}\frac{N}{60} V_{cyl} PME$$

with

$$\begin{aligned} PME &= PME_{+} - PME_{-} = \left(\int_{V_2}^{V_1} f_3(V) - f_2(V)\, dV\right) - \left(\int_{V_1}^{V_2} f_1(V) - P_{adm}\, dV\right) \\ &= \frac{1}{2}(V_2^2 - V_1^2)(a_3 - a_1 - a_2) + (V_2 - V_1)(b_3 - b_1 - b_2 + P_{adm}) \end{aligned}$$

The W_{cyl} expression can be written:

$$W_{cyl}(Q, m_p, R, T_{comb}) = \frac{N}{340} V_{cyl}^2 \Big(P_{comb} - P_{compress} + P_{adm} - P_{Exhaust} \Big) \quad (2)$$

Outlet pressure engine $P_{Exhaust}$ can be written

$$P_{Exhaust} = P^{ENG,out} = P^{ATM} + \varDelta P^{SIL}(Q) + \varDelta P^{DPF}(Q, m_p) + \varDelta P^{CT}(Q)$$

where Q is the flow rate engine and m_p is the mass of particles in the filter.

3 Modeling of particle filter

3.1 State of the art of modeling filter

The literature on modeling the pressure drop at particle filter is abundant. Among works on this topic, we want to point out the 2D model developed by [3]. The authors apply the conservation-equations of mass and momentum as well as behavioral laws (ideal gas law, Darcy's law, equations of filtration ...) in order to establish a 2D model of the charge loss on the DPF cell. This kind of models (we can also cite the thesis of [4]) are interesting to study the behavior of gas flow and the particulate filter as well as for determining the filtration phenomena. However their model can't be embedded on an industrial computer. In the following, we shall elaborate a simple model suitable for industrial purpose.

3.2 Modeling of loading particulate filter without passive regeneration

To model the DPF pressure drop, we work at the level of two channels of DPF; an entering channel and an outgoing channel as shown in Figure 2.

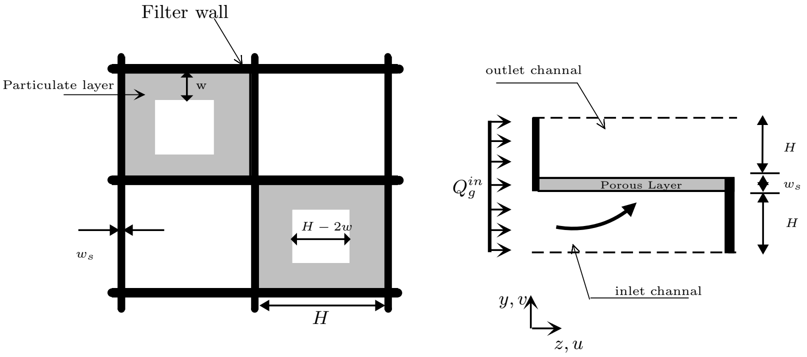

Fig. 2. A particle filter section

The pressure drop in the particle filter can be written :

$$\Delta P^{DPF} = \Delta P_{inlet} + \Delta P_{wall} + \Delta P_{soot\ layer} + \Delta P_{outlet}$$

The term ΔP_{inlet} represents the loss of horizontal friction at one input channel of the particle filter: $\Delta P_{inlet} = \dfrac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\left(\frac{4C_3L^2}{3(H-2w)^4}\right)$ where Q_{vol} denotes gases volumetric flow rate. It can be written according to the mass flow rate thanks to the relation: $Q_{vol} = \dfrac{Q}{\rho_g}$. μ denotes gases viscosity.
The term ΔP_{outlet} represents the loss of horizontal friction at an output of the particulate filter: $\Delta P_{outlet} = \dfrac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\left(\frac{4C_3L^2}{3H^2}\right)$.
The terme ΔP_{wall} represents the loss of vertical load through the porous particle filter, it is determined through Darcy's law: $\Delta P_{wall} = \dfrac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\left(\frac{w_s}{k_sH}\right)$.
The term $\Delta P_{soot\ layer}$ represents the loss of vertical load through the layer of collected soot, it is determined by the Darcy's law: $\Delta P_{soot\ layer} = \dfrac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\frac{1}{2k_w}\ln\left(\frac{H}{H-2w}\right)$.
Let's now determine the relationship between the height and the mass of particles. For a mass of stored soot (m_p) we have $m_p = \rho_p V_{ol}$ which comes to $4\rho_p L\left[w(H-2w)+w^2\right] = \dfrac{m_p}{N}$. The relationship between the height of the amount of soot collected on the porous wall and the mass of soot is thus given

by $w = \dfrac{H - \sqrt{H^2 - \dfrac{m_p}{\rho_p N L}}}{2}$. In addition $Q = \rho_g Q_{vol}$. Thus we can write

$$\begin{aligned}
\Delta P^{DPF} &= \frac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\left(\frac{4C_3L^2}{3(H-2w)^4}\right) + \frac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\left(\frac{4C_3L^2}{3H^2}\right) \\
&+ \frac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\left(\frac{w_s}{k_sH} + \frac{\mu Q_{vol}}{2V_{trap}}(H+w_s)^2\frac{1}{2k_w}\ln\frac{H}{H-2w}\right) \\
&= f_P^0(m_p, Q_{vol}, T_g^{DPF,in})
\end{aligned} \tag{3}$$

3.3 Passive regeneration DPF modeling:

When emissions of nitrogen oxides (NO_x) from motor are high enough, they react with the particles staked in the DPF. Holes in the layer of particles appear in some channels of DPF in particular in channel where the temperature is the highest. We know from the literature (see [5, 6]) that the hottest areas of DPF are on the ends of radial DPF [4].

In passive regeneration, we can see a DPF pressure drop. To model this phenomenon, we decompose the DPF in two areas as shown by Figure3.

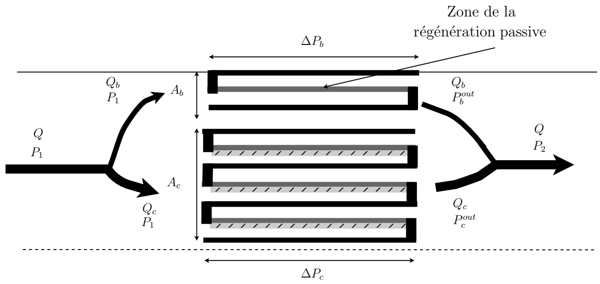

Fig. 3. Passive regeneration area

Using this DPF partition, we can determine the total pressure drop filter according to the pressure drop part in the regeneration area and the pressure drop in the other area. For that purpose, we use pressure drops modeling of a pipeline network (See [7]).

Notation:

- A_b denotes section of gas flow through the area where passive regeneration occurs . A_c denotes section of gas flow through the area at the DPF center.

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[4] The reason is that in these regions the gas velocity is low and therefore the heat dissipation is lower

- Q the total flow rate of gases which gets through the DPF. Q_b the volume flow rate which passes in the passive regeneration area. Q_c the volume flow rate which passes by the area in the center.
- P_1 and P_2 are the inlet pressures respectively outlet pressure of the DPF. P_b^{out} pressure of the regeneration zone. P_c^{out} outlet pressure area in the center. ΔP_b pressure drop between the inlet and outlet of the regeneration zone. ΔP_c pressure drop between the inlet and outlet of the area in the center.

We assume that the inlet pressure of the regeneration zone (P_b^{in}) and the inlet pressure of the area in the center (P_c^{in}) are equal to the inlet pressure of the DPF (P_1). The flow rates Q_c and Q_b are expressed as follows [5]:

$$Q_i = \frac{\sqrt{P_2 - P_i^{out}}}{\sqrt{R_i}} \qquad i \in \{c, b\} \tag{4}$$

with $R_c = \dfrac{\xi}{2\rho A_c^2}$ and $R_b = \dfrac{\xi}{2\rho A_b^2}$.
linearisation of (4) around a nominal ΔP_{nom} pressure gives:

$$Q_i = \frac{P_2 - P_i^{out}}{Z_i} \qquad i \in \{c, b\} \tag{5}$$

with $Z_i = \dfrac{1}{\sqrt{\Delta P_{nom} R_i}} \qquad i \in \{c, b\}$.
Besides, we have:

$$P_2 - P_i^{out} = \Delta P - \Delta P_i \qquad i \in \{c, b\}$$

The DPF pressure drop can be written then as:

$$\Delta P^{DPF} = \frac{Z_c}{Z_c + Z_b}\Delta P_b + \frac{Z_b}{Z_c + Z_b}\Delta P_c + \frac{Z_b Z_c}{Z_c + Z_b} Q_{vol} \tag{6}$$

From the pressure drop expression without passive regeneration (3), we can write:

$$\Delta P_c = Q_c f_c(m_p, T_g^{DPF,in}) \ , \ \Delta P_b = Q_b f_b(T_g^{DPF,in})$$

From (5) we have:

$$Q_i = \frac{Z_i}{Z_i + f_i}\Delta P \qquad i \in \{c, b\}$$

When we report this relation in the (6) equation, we obtain:

$$\Delta P\left(1 - \frac{Z_c Z_b f_c}{(Z_c + Z_b)(Z_c + f_c)} - \frac{Z_c Z_b f_b}{(Z_c + Z_b)(Z_b + f_b)}\right) = \frac{Z_b Z_c}{Z_c + Z_b} Q_{vol}$$

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[5] We consider the following causality: the pressure and the pressure Pout c Pout b impose the outlet pressure P2 (analogy with pipeline networks)

In conclusion:

$$\mathit{\Delta} P = \frac{(Z_c + f_c)(Z_b + f_b)}{Z_{cbf}} Q_{vol} = f_P(m_p, Q, T_g^{DPF}, [NO], [NO_2])$$

with $Z_{cbf} = f_Z(Z_c, Z_b, f_c, f_b)$.

Now, we have to determine A_c and A_b according to initial soot mass and the mass of soot that had react with NO$_x$. Thus, let's denote m_p^t the mass of soot that had react with NO$_x$ and consider $C_s = \frac{m_p^t}{m_p}$. we have:

$$A_b = C_s A_g, A_c = A_g - A_b$$

A_g is the section of DPF through which exhaust engine gas pass. m_p^t is give by:

$$m_p^t = a_0(T) m_p^{a_1} [NO]^{a_2} + a_3(T) m_p^{a_4} [NO_2]^{a_5}$$

We can found values of $a_0, \ldots, a_5$ in [8]

3.4 Synthesis of a loaded DPF model

The particle filter allows to collect almost totality of particles resulting from the engine [6]([9]). The quantity of soot $Q_{soot}^{ENG,out}$ emitted by the engine can be given by the formula:$Q_{soot}^{ENG,out} = g_M(R, N, \mathit{\Gamma}_r, T_g^{ENG,in}, T_e^{ENG,in})$. For the modelling of the quantity of particle in motor outlet we can quote [10, 11]. We can then write a dynamic model which describes the pressure drop of the DPF for a given driving operating point.

$$\begin{aligned} \frac{dm_p}{dt} &= g_M(R, N, \mathit{\Gamma}_r, T_g^{ENG,in}, T_e^{ENG,in}) - a_0(T) m_p^{a_1} [NO]^{a_2} + a_3(T) m_p^{a_4} [NO_2]^{a_5} \\ \mathit{\Delta} P^{DPF} &= f_P(m_p, Q, T_g^{DPF}, [NO], [NO_2]) \end{aligned} \tag{7}$$

3.5 Unloading model of particle filter

In the literature, one can find many studies whose objective is to develop and to validate a model of regeneration of the filter with Diesel particle. We can mention the 0D model of [12], taken back in [13–15]. We found in [16] a 1D extension of this model. To model the unloading of DPF we use the model developed by IFP[7] [17] and improved in [18]. According to [18] and [19], the thickness of the soot layer evolves according to the equation:

$$\rho_p \frac{\partial w}{\partial t} = g_R(Y_1, P_1, P_2, w)$$

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[6] . The efficiency of the DPF increases with time. The filtration coefficient of the porous wall is over 90% after some hours of use. .

[7] Institue Franais de Pétrole

with:

$$g_R = \frac{M_c}{M_{O_2}} \frac{\phi_w}{H-2w} \left((Y_1^{1-\alpha} + \frac{(1-\alpha)B}{\alpha+2} (P_{int}^{\alpha+2} - P_1^{\alpha+2}))^{\frac{1}{1-\alpha}} - Y_1 \right)$$

$$\begin{aligned} P_{int} &= P_w(w) &\approx \sqrt{\frac{k_s w_s P_1^2 + k_w w P_2^2}{k_s w_s + k_w w}} \\ \phi_w &= \rho_w v_w d(y) = &\frac{P_1^2 - P_2^2}{\frac{2\mu r T_w}{H} (\frac{w}{k_w} - \frac{w_s}{k_s})} \end{aligned}$$

P_1 denotes the pressure in the channel filter input and P_2 is the pressure at the outlet. Y_1 is the mass fraction of oxygen in the inlet of the DPF.

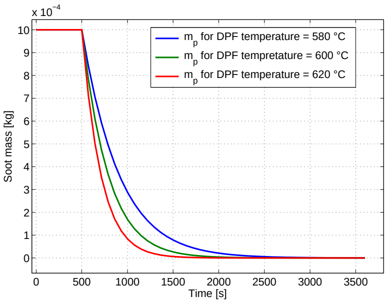

Fig. 4. Soot DPF active regeneration.

3.6 Synthesis of a particle filter model

According to the correlation between height and mass of particles in the DPF subsection 3.2, we can write: $\alpha_m \frac{dm_p}{dt} = H - 2w \frac{dw}{dt}$ with $\alpha_m = \frac{1}{4\rho_p N L}$. We propose here a model that combines the phases of DPF loading and unloading:

$$\begin{aligned} \frac{dm_p}{dt} &= g_M(R, N, \mathit{\Gamma}_r, T_g^{ENG,in}, T_e^{ENG,in}) - a_0(T) m_p^{a_1} [NO]^{a_2} - a_3(T) m_p^{a_4} [NO_2]^{a_5} + g_R(Y_1, P_1, P_2, w) \\ \mathit{\Delta} P^{DPF} &= f_P(m_p, Q, T_g^{DPF}, [NO], [NO_2]) \end{aligned}$$

4 Models validation

4.1 Identification

From the various performed tests we were able to identify the model parameters. We subsequently used other sample trials for validation. The vector $V_{par} =$

$\left(k_s \; k_w \; C_3 \; a_0..a_5 \right)^T$ represent the identification model parameters. The identification task is to find the vector V_{par} that minimizes the following least squares criterion:

$$J(\mathbf{V_{par}}) = \sum_{i,j} (\mathit{\Delta} P_{i,j}^{mes} - \mathit{\Delta} P_{i,j}^{mdl}(\mathbf{V_{par}}))^2$$

with $\mathit{\Delta} P_{i,j}^{mes}$ pressure drop for the test number j at the time $t = i$ and $\mathit{\Delta} P_{i,j}^{mdl}(\mathbf{V_{par}})$ pressure drop model.

4.2 Correlation with experiments:

Several series of tests are performed. Some of these tests are on engine test benches, they are essentially static tests. Other tests are performed on a dynamometer, or directly on vehicles; which are essentially dynamic tests. We illustrate some examples of validation of our models.
Some permanent validations:

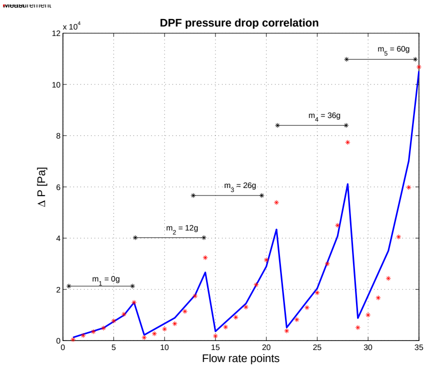

Fig. 5. Validation for a 2,8 liter DPF

Some dynamic validation (500km cycle):

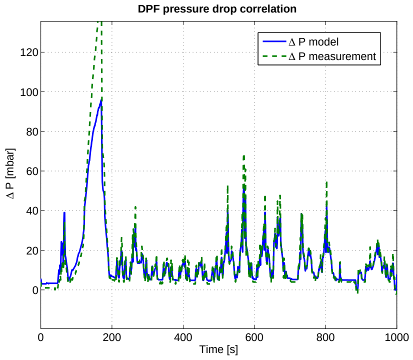

Fig. 6. 0 to 1000s correlation

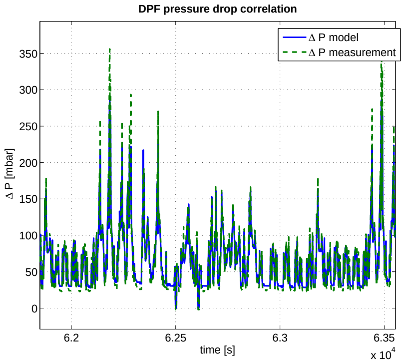

Fig. 7. Middle of experiment

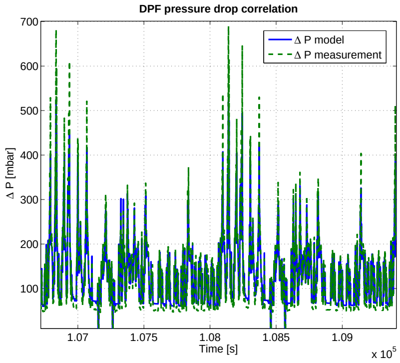

Fig. 8. End of experiment

On the figure 9, we draw curves of the model pressures against measure results. We notice, that in case where the passive regeneration happen, the model with passive regeneration developed in the part 3.2 fits well.

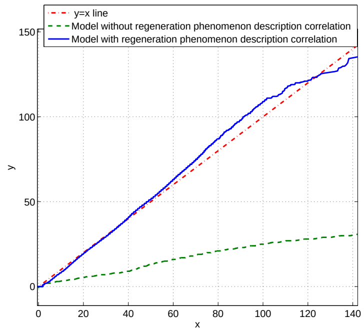

Fig. 9. Model comparison w/wo passive regeneration

5 Conclusion and outlook

In this article we expressed the mechanical power of the engine according to the flow rate of combustion gases, the pressure drop of the engine and the mass of soot in the particulate filter. This expression permits to quantify the impact of filter loading on the engine performance. This allows optimizing the calculation of the mass of soot limit from which the filter must be regenerated. Then we presented, filters pressure drop model based on expressions of regular pressure losses and the Darcy law for porous walls. We are afterward inspired by the literature on thermal regeneration of the DPF and by literature on pipeline pressure drop to propose a model of the DPF in presence of passive regeneration. All the experimental validations are made thanks to different configuration: engine dynamometer, chassis dynamometer and vehicles.

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